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Hadronic production of B_c-mesons

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Abstract On the basis of the exact formulas of QCD perturbation theory and parton model the hadronic production cross-sections for $B_c(B_c{}^*)$-mesons ($1^1S_0, 1^3S_1, 2^1S_0, 2^3S_1$-states) are calculated. The method used is the direct calculation of appropriate amplitudes with the help of a FORTRAN program and subsequent Monte-Carlo integration over the phase space and convolution with the structure functions.

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Introduction.

Recently, there has been much interest in the study of B-mesons. In the nearest future the CP-breaking parameters are planned to be determined which suggests the production of $10^9 - 10^{10}$ B-mesons. In these experiments the study of B_c-mesons, consisting of b- and $\bar{c}$-quarks, will also be possible. The B_c production cross-section in comparison with that of B-mesons is suppressed approximately by three orders. Hence, having $10^6 - 10^7$ B_c-mesons one may hope to study in detail the properties of the $b\bar{c}$ system.

In a number of works [1-5] (see also more earlier works [6-10]), devoted to the production of B_c-mesons and their exciting states in e^+e^- annihilation it is shown that the process of $B_c(B_c^*)$-meson production at high energies can be represented as b-quark fragmentation into B_c-meson. The analytical expression for the fragmentation function $D_{b\to B_c}(z)$ and relative probability of $\sim 10^{-3}$ is obtained, which allows one to relate the process of B_c-meson production with the production of $b\bar{b}$ pair with large invariant mass.

In e^+e^- annihilation the production cross-section of B_c-mesons is related with that of b-quarks in the following way

$$\frac{d\sigma_{e^+e^-\to B_c(B_c^*)\bar{b}c}}{dz} = \sigma_{e^+e^-\to b\bar{b}} \cdot D_{b\to B_c(B_c^*)}(z). \tag{1}$$

where $z = |\vec{p}|/2\sqrt{s}$, $\vec{p}$ — momentum of B_c-meson, $\sqrt{s}$ — total energy squared of e^+e^- pair, $D_{b\to B_c}(z)$ and $D_{b\to B_c^*}(z)$ — fragmentation functions, while $\sigma_{e^+e^-\to b\bar{b}}$ — cross-section of the process $e^+e^- \to b\bar{b}$, calculated in Born approximation.

One should note, however, that factorized form (1) in e^+e^- annihilation is realized when $M^2_{B_c}/s$ is small. Hence, form (1) could be realized in hadronic production only for large $p_\perp$ of B_c-meson. The final answer in the case of hadronic production of B_c-mesons turns out to be more complex. First, in hadronic production the region of small invariant masses dominates, where the asymptotical regime with the cross-section factorization (1) is not realized yet. Second, for hadronic interactions the new type of diagram appears (called further recombination diagrams) for which such factorization is absent. The contribution of these diagrams, dominating at small invariant masses of the $B_c\bar{b}c$ system, falls with the increase of this mass, but for all studied energies is substantial. As the result of exact numerical calculations of matrix elements we will show that for reasonable values of the B_c-mesons transverse momenta , produced at hadron colliders, the contributions of both fragmentation and recombination types are significant. For small transverse momenta the last one dominates.

The work is organized as follows. In the first Section the procedure of matrix element calculation is presented. The behavior of differential cross-sections of the subprocess $gg \to B_c\bar{b}c$ as a function of total gluon energy is discussed in the second Section. To obtain the cross-section of B_c-mesons in hadronic collisions we convolute in Section 3 $\hat{\sigma}_{gg\to B_c\bar{b}c}$ with structure functions of gluons in initial hadrons.

1 Calculation method.

On the tree level the subprocess

is described by 38 Feynmann diagrams, that can be restored from Fig. 1 and Table 1. As in [1,3,11] the amplitudes can conveniently be calculated by direct numerical multiplication of γ-matrixes, spinors and polarization vectors.

Let us introduce the following notions:

$$q_1^2 = q_2^2 = m_1^2 = m_2^2 = m_b^2, \qquad q_3^2 = q_4^2 = m_3^2 = m_4^2 = m_c^2,$$
$$q_{12} = -q_1 - q_2, \qquad q_{34} = -q_3 - q_4, \qquad p_{12} = p_1 + p_2,$$
$$k_1 = p_1 + q_{12}, \qquad k_2 = p_1 + q_{34}$$

The three gluon vertexes are used in the form:

$$\Gamma^\mu(p_a, p_b, \epsilon_a, \epsilon_b) = -\Big((2p_a + p_b)\cdot\epsilon_b\Big)\epsilon_a^\mu + (p_a - p_b)^\mu\Big(\epsilon_a\cdot\epsilon_b\Big) + \Big((2p_b + p_a)\cdot\epsilon_a\Big)\epsilon_b^\mu,$$
$$\Gamma'^\mu(p_a, p_b, \epsilon_a, \epsilon_b) = \Gamma^\mu(p_a, p_b, \epsilon_a, \epsilon_b)/(p_a + p_b)^2$$

Two quark currents are defined as follows:

$$J_{12}^\mu = \frac{\bar{u}(q_1)\gamma^\mu v(q_2)}{q_{12}^2} \qquad J_{34}^\mu = \frac{\bar{u}(q_3)\gamma^\mu v(q_4)}{q_{34}^2}.$$

Besides, let us introduce subsidiary spinors:

$$\bar{u}_{ij} = \bar{u}(q_i)\hat{\epsilon}_j\frac{(\hat{q}_i - \hat{p}_j + m_i)}{(q_i - p_j)^2 - m_i^2} \qquad v_{ij} = \frac{(\hat{p}_j - \hat{q}_i + m_i)}{(p_j - q_i)^2 - m_i^2)}\hat{\epsilon}_j v(q_i)$$

$$\bar{u}_{1,34} = \frac{\bar{u}(q_1)\hat{J}_{34}(\hat{q}_1 - \hat{q}_{34} + m_1)}{(q_1 - q_{34})^2 - m_1^2} \qquad \bar{u}_{3,12} = \frac{\bar{u}(q_3)\hat{J}_{12}(\hat{q}_3 - \hat{q}_{12} + m_3)}{(q_3 - q_{12})^2 - m_3^2}$$

$$v_{2,34} = \frac{(\hat{q}_{34} - \hat{q}_2 + m_2)\hat{J}_{34}v(q_2)}{(q_{34} - q_2)^2 - m_2^2} \qquad v_{4,12} = \frac{(\hat{q}_{12} - \hat{q}_4 + m_4)\hat{J}_{12}v(q_4)}{(q_{12} - q_4)^2 - m_4^2}.$$

Gluon polarization vectors are used in the following way:

$$\epsilon_1 = \epsilon_1(p_1) \qquad \epsilon_2 = \epsilon_2(p_2).$$

The matrix element squared are summed over orthogonal gluon states:

$$\epsilon' = (0, 1, 0, 0) \;\; \epsilon'' = (0, 0, 1, 0).$$

Note, that $\epsilon'^2 = \epsilon''^2 = -1$, and $p \cdot \epsilon = 0$, where p - gluon momentum. For colour indexes we use notions:

upper index g_1, g_2–gluons;
lower index q_1–b-quark;
lower index q_2–$\bar{b}$-quark;
lower index q_3–c-quark;
lower index q_4–$\bar{c}$-quark.

The contributions from appropriate diagrams (see Fig. 1 and Tab. 1) will have the following forms (colour coefficients are surrounded by braces):

$$M_1 = \Big(\Gamma(p_2, q_{34}, \epsilon_2, J_{34}) \cdot \Gamma'(p_1, q_{12}, \epsilon_1, J_{12})\Big) \cdot \{f^{k_1 g_2 k_2} f^{k_3 k_2 g_1} t^{k_1}_{q_3 q_4} t^{k_3}_{q_1 q_2}\}$$
$$M_2 = \Big(\Gamma'(p_1, q_{34}, \epsilon_1, J_{34}) \cdot \Gamma(p_2, q_{12}, \epsilon_2, J_{12})\Big) \cdot \{f^{k_1 g_2 k_2} f^{k_3 k_2 g_1} t^{k_3}_{q_3 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_3 = \Big(\Gamma'(p_1, p_2, \epsilon_1, \epsilon_2) \cdot \Gamma(q_{12}, q_{34}, J_{12}, J_{34})\Big) \cdot \{-f^{k_1 g_2 g_1} f^{k_2 k_1 k_3} t^{k_2}_{q_1 q_2} t^{k_3}_{q_3 q_4}\}$$
$$M_4 = J^{\alpha}_{12} J^{\beta}_{34} \Big(\epsilon_{1\beta}\epsilon_{2\alpha} - (\epsilon_1 \cdot \epsilon_2) g_{\alpha\beta}\Big) \cdot \{f^{k_1 g_2 k_2} f^{k_2 k_3 g_1} t^{k_3}_{q_1 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_5 = J^{\alpha}_{12} J^{\beta}_{34} \Big((\epsilon_1 \cdot \epsilon_2) g_{\alpha\beta} - \epsilon_{1\alpha}\epsilon_{2\beta}\Big) \cdot \{f^{g_2 k_1 k_2} f^{k_2 k_3 g_1} t^{k_1}_{q_1 q_2} t^{k_3}_{q_3 q_4}\}$$
$$M_6 = J^{\alpha}_{12} J^{\beta}_{34} \Big(\epsilon_{1\alpha}\epsilon_{2\beta} - \epsilon_{1\beta}\epsilon_{2\alpha}\Big) \cdot \{f^{k_1 k_2 k_3} f^{k_3 g_2 g_1} t^{k_1}_{q_1 q_2} t^{k_2}_{q_3 q_4}\}$$
$$M_7 = \bar{u}_{11} \hat{\Gamma}'(p_2, q_{34}, \epsilon_2, J_{34}) v(q_2) \cdot \{i f^{k_1 k_2 g_2} t^{k_1}_{q_3 q_4} t^{g_1}_{q_1 l_1} t^{k_2}_{l_1 q_2}\}$$
$$M_8 = \bar{u}(q_1) \hat{\Gamma}'(p_2, q_{34}, \epsilon_2, J_{34}) v_{21} \cdot \{i f^{k_1 k_2 g_2} t^{k_1}_{q_3 q_4} t^{k_2}_{q_1 l_1} t^{g_1}_{l_1 q_2}\}$$
$$M_9 = \bar{u}_{31} \hat{\Gamma}'(p_2, q_{12}, \epsilon_2, J_{12}) v(q_4) \cdot \{i f^{k_1 k_2 g_2} t^{k_1}_{q_1 q_2} t^{g_1}_{q_3 l_1} t^{k_2}_{l_1 q_4}\}$$
$$M_{10} = \bar{u}(q_3) \hat{\Gamma}'(p_2, q_{12}, \epsilon_2, J_{12}) v_{41} \cdot \{i f^{k_1 k_2 g_2} t^{k_1}_{q_1 q_2} t^{k_2}_{q_3 l_1} t^{g_1}_{l_1 q_4}\}$$
$$M_{11} = \bar{u}(q_3) \hat{\Gamma}'(p_1, q_{12}, \epsilon_1, J_{12}) v_{42} \cdot \{i f^{k_1 k_2 g_1} t^{k_1}_{q_1 q_2} t^{k_2}_{q_3 l_1} t^{g_2}_{l_1 q_4}\}$$
$$M_{12} = \bar{u}_{32} \hat{\Gamma}'(p_1, q_{12}, \epsilon_1, J_{12}) v(q_4) \cdot \{i f^{k_1 k_2 g_1} t^{k_1}_{q_1 q_2} t^{g_2}_{q_3 l_1} t^{k_2}_{l_1 q_4}\}$$

$$M_{13} = \bar{u}(q_1) \hat{\Gamma}'(p_1, q_{34}, \epsilon_1, J_{34}) v_{22} \cdot \{i f^{k_1 k_2 g_1} t^{k_1}_{q_3 q_4} t^{k_2}_{q_1 l_1} t^{g_2}_{l_1 q_2}\}$$
$$M_{14} = \bar{u}_{12} \hat{\Gamma}'(p_1, q_{34}, \epsilon_1, J_{34}) v(q_2) \cdot \{i f^{k_1 k_2 g_1} t^{k_1}_{q_3 q_4} t^{g_2}_{q_1 l_1} t^{k_2}_{l_1 q_2}\}$$
$$M_{15} = \bar{u}_{11} \gamma^{\alpha} v(q_2) \bar{u}(q_3) \gamma_{\alpha} v_{42} / k_1^2 \cdot \{t^{g_1}_{q_1 l_1} t^{k_1}_{l_1 q_2} t^{k_1}_{q_3 l_2} t^{g_2}_{l_2 q_4}\}$$
$$M_{16} = \bar{u}(q_1) \gamma^{\alpha} v_{21} \bar{u}(q_3) \gamma_{\alpha} v_{42} / k_1^2 \cdot \{t^{k_1}_{q_1 l_1} t^{g_1}_{l_1 q_2} t^{k_1}_{q_3 l_2} t^{g_2}_{l_2 q_4}\}$$
$$M_{17} = \bar{u}_{11} \gamma^{\alpha} v(q_2) \bar{u}_{32} \gamma_{\alpha} v(q_4) / k_1^2 \cdot \{t^{g_1}_{q_1 l_1} t^{k_1}_{l_1 q_2} t^{g_2}_{q_3 l_2} t^{k_1}_{l_2 q_4}\}$$
$$M_{18} = \bar{u}(q_1) \gamma^{\alpha} v_{21} \bar{u}_{32} \gamma_{\alpha} v(q_4) / k_1^2 \cdot \{t^{k_1}_{q_1 l_1} t^{g_1}_{l_1 q_2} t^{g_2}_{q_3 l_2} t^{k_1}_{l_2 q_4}\}$$
$$M_{19} = \bar{u}_{31} \gamma^{\alpha} v(q_4) \bar{u}(q_1) \gamma_{\alpha} v_{22} / k_2^2 \cdot \{t^{k_1}_{q_1 l_1} t^{g_2}_{l_1 q_2} t^{g_1}_{q_3 l_2} t^{k_1}_{l_2 q_4}\}$$
$$M_{20} = \bar{u}(q_3) \gamma^{\alpha} v_{41} \bar{u}(q_1) \gamma_{\alpha} v_{22} / k_2^2 \cdot \{t^{k_1}_{q_1 l_1} t^{g_2}_{l_1 q_2} t^{k_1}_{q_3 l_2} t^{g_1}_{l_2 q_4}\}$$
$$M_{21} = \bar{u}_{31} \gamma^{\alpha} v(q_4) \bar{u}_{12} \gamma_{\alpha} v(q_2) / k_2^2 \cdot \{t^{g_2}_{q_1 l_1} t^{k_1}_{l_1 q_2} t^{g_1}_{q_3 l_2} t^{k_1}_{l_2 q_4}\}$$
$$M_{22} = \bar{u}(q_3) \gamma^{\alpha} v_{41} \bar{u}_{12} \gamma_{\alpha} v(q_2) / k_2^2 \cdot \{t^{g_2}_{q_1 l_1} t^{k_1}_{l_1 q_2} t^{k_1}_{q_3 l_2} t^{g_1}_{l_2 q_4}\}$$
$$M_{23} = \bar{u}_{1,34} \hat{\epsilon}_1 v_{22} \cdot \{t^{k_1}_{q_1 l_1} t^{g_1}_{l_1 l_2} t^{g_2}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{24} = \bar{u}_{11} \hat{J}_{34} v_{22} \cdot \{t^{g_1}_{q_1 l_1} t^{k_1}_{l_1 l_2} t^{g_2}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{25} = \bar{u}_{11} \hat{\epsilon}_2 v_{2,34} \cdot \{t^{g_1}_{q_1 l_1} t^{g_2}_{l_1 l_2} t^{k_1}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{26} = \bar{u}_{1,34} \hat{\epsilon}_2 v_{21} \cdot \{t^{k_1}_{q_1 l_1} t^{g_2}_{l_1 l_2} t^{g_1}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{27} = \bar{u}_{12} \hat{J}_{34} v_{21} \cdot \{t^{g_2}_{q_1 l_1} t^{k_1}_{l_1 l_2} t^{g_1}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{28} = \bar{u}_{12} \hat{\epsilon}_1 v_{2,34} \cdot \{t^{g_2}_{q_1 l_1} t^{g_1}_{l_1 l_2} t^{k_1}_{l_2 q_2} t^{k_1}_{q_3 q_4}\}$$
$$M_{29} = \bar{u}_{3,12} \hat{\epsilon}_1 v_{42} \cdot \{t^{k_1}_{q_3 l_1} t^{g_1}_{l_1 l_2} t^{g_2}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{30} = \bar{u}_{31} \hat{J}_{12} v_{42} \cdot \{t^{g_1}_{q_3 l_1} t^{k_1}_{l_1 l_2} t^{g_2}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{31} = \bar{u}_{31} \hat{\epsilon}_2 v_{4,12} \cdot \{t^{g_1}_{q_3 l_1} t^{g_2}_{l_1 l_2} t^{k_1}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{32} = \bar{u}_{3,12} \hat{\epsilon}_2 v_{41} \cdot \{t^{k_1}_{q_3 l_1} t^{g_2}_{l_1 l_2} t^{g_1}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{33} = \bar{u}_{32} \hat{J}_{12} v_{41} \cdot \{t^{g_2}_{q_3 l_1} t^{k_1}_{l_1 l_2} t^{g_1}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{34} = \bar{u}_{32} \hat{\epsilon}_1 v_{4,12} \cdot \{t^{g_2}_{q_3 l_1} t^{g_1}_{l_1 l_2} t^{k_1}_{l_2 q_4} t^{k_1}_{q_1 q_2}\}$$
$$M_{35} = \bar{u}_{1,34} \hat{\Gamma}'(p_1, p_2, \epsilon_1, \epsilon_2) v(q_2) \cdot \{-i f^{k_1 g_2 g_1} t^{k_2}_{q_1 l_1} t^{k_1}_{l_1 q_2} t^{k_2}_{q_3 q_4}\}$$
$$M_{36} = \bar{u}(q_1) \hat{\Gamma}'(p_1, p_2, \epsilon_1, \epsilon_2) v_{2,34} \cdot \{-i f^{k_1 g_2 g_1} t^{k_1}_{q_1 l_1} t^{k_2}_{l_1 q_2} t^{k_2}_{q_3 q_4}\}$$
$$M_{37} = \bar{u}_{3,12} \hat{\Gamma}'(p_1, p_2, \epsilon_1, \epsilon_2) v(q_4) \cdot \{-i f^{k_1 g_2 g_1} t^{k_2}_{q_3 l_1} t^{k_1}_{l_1 q_4} t^{k_2}_{q_1 q_2}\}$$
$$M_{38} = \bar{u}(q_3) \hat{\Gamma}'(p_1, p_2, \epsilon_1, \epsilon_2) v_{4,12} \cdot \{-i f^{k_1 g_2 g_1} t^{k_1}_{q_3 l_1} t^{k_2}_{l_1 q_4} t^{k_2}_{q_1 q_2}\}$$

Table 1: The correspondence between the diagrams of Fig. 1 and the contributions M_α in the total four free quarks gluonic production amplitudes.

α	the diagram	a	b	1	2	α	the diagram	a	b	1	2
1	1	1	2	$b\bar b$	$c\bar c$	20	7	2	1	$b\bar b$	$c\bar c$
2	1	2	1	$b\bar b$	$c\bar c$	21	8	2	1	$c\bar c$	$b\bar b$
3	2	1	2	$b\bar b$	$c\bar c$	22	6	2	1	$b\bar b$	$c\bar c$
4	11	1	2	$b\bar b$	$c\bar c$	23	12	1	2	$b\bar b$	$c\bar c$
5	11	1	2	$b\bar b$	$c\bar c$	24	5	1	2	$b\bar b$	$c\bar c$
6	11	1	2	$b\bar b$	$c\bar c$	25	13	2	1	$b\bar b$	$c\bar c$
7	9	1	2	$b\bar b$	$c\bar c$	26	12	2	1	$b\bar b$	$c\bar c$
8	10	1	2	$b\bar b$	$c\bar c$	27	5	2	1	$b\bar b$	$c\bar c$
9	9	1	2	$c\bar c$	$b\bar b$	28	13	1	2	$b\bar b$	$c\bar c$
10	10	1	2	$c\bar c$	$b\bar b$	29	12	1	2	$c\bar c$	$b\bar b$
11	10	2	1	$c\bar c$	$b\bar b$	30	5	1	2	$c\bar c$	$b\bar b$
12	9	2	1	$c\bar c$	$b\bar b$	31	13	2	1	$c\bar c$	$b\bar b$
13	10	2	1	$b\bar b$	$c\bar c$	32	12	2	1	$c\bar c$	$b\bar b$
14	9	2	1	$b\bar b$	$c\bar c$	33	5	2	1	$c\bar c$	$b\bar b$
15	6	1	2	$b\bar b$	$c\bar c$	34	13	1	2	$c\bar c$	$b\bar b$
16	7	1	2	$b\bar b$	$c\bar c$	35	4	1	2	$b\bar b$	$c\bar c$
17	8	1	2	$b\bar b$	$c\bar c$	36	3	1	2	$b\bar b$	$c\bar c$
18	6	2	1	$c\bar c$	$b\bar b$	37	4	1	2	$c\bar c$	$b\bar b$
19	6	1	2	$c\bar c$	$b\bar b$	38	3	1	2	$c\bar c$	$b\bar b$

One can represent the matrix element of the given subprocess in the following form:

$$M_{gg} = \sum_{\alpha=1}^{38} M_\alpha = \sum_{\alpha=1}^{38} C_\alpha \cdot \tilde M_\alpha,$$

where $\tilde M_\alpha$ is a spinor part of the contribution of the diagram with number α, C_α–colour part and $M_\alpha = C_\alpha \cdot \tilde M_\alpha$ is the total contribution of the appropriate diagram.

The matrix element squared for the subprocess $gg \to b\bar b c\bar c$ is obtained from the formula:

$$|M_{gg}|^2 = (4\pi\alpha_s)^4 \cdot \sum_{\mu_i,\lambda_j} \Big(\sum_{\alpha,\beta} \tilde M^*_\alpha(\mu_i,\lambda_j) C_{\alpha\beta} \tilde M_\beta(\mu_i,\lambda_j) \Big),$$

where μ_i–polarization states of initial gluons, λ_j– a set of helicity states of final fermions, $\tilde M_\gamma$– helicity part of the contribution from the appropriate Feynmann diagram, $C_{\alpha\beta}$– colour matrix calculated by a separate program by using the formula:

$$C_{\alpha\beta} = \sum_{i_1,i_2,f_1,f_2,f_3,f_4} C^*_\alpha(i_1,i_2,f_1,f_2,f_3,f_4) \cdot C_\beta(i_1,i_2,f_1,f_2,f_3,f_4),$$

where i_1, i_2–colour states of initial partons, f_1, f_2, f_3, f_4–colour states of final quarks and C_γ– colour part of the appropriate Feynmann diagram. The cross-section of the subprocess under consideration is obtained through Monte-Carlo integration over the phase space of $b\bar b c\bar c$ particles and averaging over the colour and helicity states of initial gluons.

An analogous calculation method can also be used for the subprocess $q\bar q \to b(q_1) +$

2 B_c-meson production cross-section.

We confine ourselves to the consideration of the S-wave states of B_c-mesons. The underlying assumption of our calculations is that the binding energy of two quarks, b, $\bar{c}$ is much less than their masses and, hence, heavy quarks in the bound state B_c are actually on the mass shell. In this case the 4-momenta p_b and p_c of the quark constituents of B_c-meson are related with the 4-momentum P of B_c-meson as follows

$$p_b = \frac{m_b}{M} P \qquad\qquad p_c = \frac{m_c}{M} P$$

where $M = m_b + m_c$ is the B_c-meson mass. Hence, the B_c-meson production is described by the diagrams of Fig. 1 by combining two quark lines to meson line and singling out the states with definite quantum numbers. The amplitude of B_c-meson production can be expressed through appropriate projection operators and helicity amplitudes $M_{h\bar{h}}(\lambda_i)$ as follows:

$$M(\lambda_i) = \frac{\sqrt{2M}}{\sqrt{2m_b}\sqrt{2m_c}} \Psi(0) \sum_{h,\bar{h},q,\bar{q}} P_{h,\bar{h}} M_{h,\bar{h},q,\bar{q}}(\lambda_i) \delta_{q,\bar{q}}$$

where summation is made over the helicity $h, \bar{h}$ and colour $q, \bar{q}$ indices of the quark and antiquark producing B_c-meson. The helicities of remaining fermions are symbolically denoted through λ_i. Projection operators $P_{h,\bar{h}}$ have the following explicit form ($H = h - \bar{h}$)[1,3,12]:

$$P_{h,\bar{h}} = \frac{1}{\sqrt{2}} (-1)^{\bar{h}-1/2} \delta_{H,0}$$

for the S_0-state and

$$P_{h,\bar{h}} = |H| + \frac{1}{\sqrt{2}} \delta_{H,0}$$

for the S_1-state.

The value of the wave function at the origin $\Psi(0)$ is calculated in the nonrelativistic potential model and also in the QCD sum rules [13] and is related with the decay constant f_{B_c} of the pseudoscalar $B_c(0^-)$-meson and constant $f_{B_c^*}$ of the vector $B_c^*(1^-)$-meson as follows:

$$\Psi(0) = \sqrt{\frac{M}{12}} f_{B_c},$$

where

$$f_{B_c} = f_{B_c^*} = 570 \text{ MeV}$$

Potentials of various types yield actually the same values of the masses of low lying states of $B_c(B_c^*)$-mesons. For example, the mass of pseudoscalar 0^--meson ($1S$-state) is $M = 6.3$ GeV. In this connection, when calculating the bound states of B_c-mesons of $1S$ levels we take the masses of b-and c-quarks somewhat larger, than those for the production of free $b\bar{b}c\bar{c}$-quarks and equal to $m_b = 4.8$ GeV and $m_c = 1.5$ GeV. The mass of $2S$ levels

Table 2: Gluon cross-section of $B_c(B_c^*)$-meson production. (Bracketed is the Monte-Carlo error in the last digit.)

	20 GeV	40 GeV	100 GeV	1 TeV
$\hat{\sigma}_{B_c}, nb$	$2.93(1) \cdot 10^{-2}$	$4.0(1) \cdot 10^{-2}$	$2.1(1) \cdot 10^{-2}$	$2.7(4) \cdot 10^{-4}$
$\hat{\sigma}_{B_c^*}, nb$	$7.16(3) \cdot 10^{-2}$	$0.105(2)$	$5.6(2) \cdot 10^{-2}$	$6(1) \cdot 10^{-4}$

be still larger: $m_b = 5.1$ GeV and $m_c = 1.8$ GeV. The value of the wave function at the origin $\Psi(0)$ for $2S$ states is $\Psi(0) = 0.275$ GeV$^{3/2}$ [14].

The calculation of the colour matrix and integration over the phase space of final particles is analogous to the case of four free quark production.

The FORTRAN program for the calculation of the matrix element was obtained by means of slight changes of the program calculating the matrix element of four free quark production. This program was checked on the Lorentz invariance with respect to boost along the beam axis and azimuthal invariance ($p_x \to p_y$ and $p_y \to -p_x$).

Table 2 and Fig. 2 show the values of $\hat{\sigma}_{gg\to B_c(B_c^*)\bar{b}c}$ for several energies of interacting gluons assuming that $m_b = 5.1$ GeV, $m_c = 1.5$ GeV and $\alpha_s = 0.2$.

We see that the ratio $\sigma_{B_c^*}/\sigma_{B_c}$ is ~ 2.5 for energies 20, 40, 100 GeV and it $\simeq 2$ for 1 TeV, while in e^+e^- annihilation [1-3] the ratio of $\sigma_{B_c^*}/\sigma_{B_c}$ is predicted to be $\simeq 1.3$. This suggests an idea that the mechanism of the $B_c(B_c^*)$-meson production on gluons is in principle different from that in the process $e^+e^- \to B_c(B_c^*)\bar{b}c$. In order to understand this difference let us consider the subprocess $gg \to B_c(B_c^*)\bar{b}c$. From Fig. 1 one can see that there are two types of diagrams. In diagrams (3), (4), (12), (13) of Fig. 1 the quark-antiquark pair is created on the leg of quark of a different flavour. We call such diagrams as fragmentation ones. As for diagrams (1), (2), (5)-(11), called recombination type diagrams, quark-antiquark pairs are created independently.

In [1,2] it was shown, that for the process $e^+e^- \to B_c\bar{b}c$ described only by fragmentation diagrams, for $\frac{M^2_{B_c}}{s} \ll 1$, the mechanism of fragmentation is realized, and for the cross-section equation (1) is right. Using the same method as in [2], one can easily show, that for the subprocess $gg \to B_c\bar{b}c$ cross-section, the contribution of fragmentation diagrams in the regime $\frac{M^2_{B_c}}{s} \ll 1$ can also, as in e^+e^- annihilation, be represented in the factorized form:

$$\frac{d\sigma_{gg\to B_c(B_c^*)\bar{b}c}}{dz} = \sigma_{gg\to b\bar{b}} \cdot D^{(*)}(z), \tag{2}$$

where functions $D(z)$ and $D^*(z)$ are the same as in the process $e^+e^- \to B_c(B_c^*)\bar{b}c$ and $\sigma_{gg\to b\bar{b}}$ is the cross-section of the process $gg \to b\bar{b}$ for the same energy.

For $D(z)$ we will use the following formulas [2,3]:

$$\begin{aligned} D(z) &= \frac{8\alpha_s^2|\Psi(0)|^2}{27m_c^3}\frac{(1-r)z(1-z)^2}{(1-rz)^6}\Big(2+(6-12r)z+(5-\frac{62}{3}r+\frac{68}{3}r^2)z^2 \\ &+ (-\frac{10}{3}r+\frac{34}{3}r^2-12r^3)z^3+(r^2-2r^3+2r^4)z^4\Big) \end{aligned} \tag{3}$$

for the pseudoscalar B_c-meson and

$$\begin{aligned} D^*(z) &= \frac{8\alpha_s^2|\Psi(0)|^2}{27m_c^3}\frac{(1-r)z(1-z)^2}{(1-rz)^6}\Big(2+(-2-4r)z+(15-18r+12r^2)z^2 \\ &+ (-10r+6r^2-4r^3)z^3+(3r^2-2r^3+2r^4)z^4\Big) \end{aligned} \tag{4}$$

for the vector B_c^*-meson.

Unfortunately, in the energy range under consideration the picture of $B_c(B_c^*)$-meson production in the process $gg \to B_c(B_c^*)\bar{b}c$ turns out to be more complex and can not be described by simple fragmentation. This can be seen from Figs. 3a, 4a, 5a, where we show the distribution of $\frac{d\hat{\sigma}_{gg\to B_c\bar{b}c}}{dz}$ (solid line), calculated by Monte-Carlo integration of the matrix element for energies 20, 40, 100 GeV, respectively, in comparison with the distribution given by (2) (dotted line).

One can see that the cross-sections are much larger than those obtained from formula (2) for energies 20, 40, 100 GeV. By dashed lines on these Figures we show the distribution $\frac{d\hat{\sigma}^{frag}_{gg\to B_c\bar{b}c}}{dz}$, calculated by means of Monte-Carlo integration of fragmentation contribution. One can see that the contribution of fragmentation diagrams already at the energy 40 GeV is described by formula (2) quite well. Fig. 4d shows both distributions of $\frac{d\hat{\sigma}^{frag}_{gg\to B_c\bar{b}c}}{dz}$ (dashed line) and $\sigma_{gg\to b\bar{b}} \cdot D(z)$ (solid line). The difference between the last two distributions is the evidence that nonscaled terms of the order of $\frac{M^2_{B_c}}{s}$ are still substantial. As is evident from Fig. 5d nonscaled terms in the fragmentation region remains also at 100 GeV.

Figs. 6a, 7a,d, 8a,d show the same distributions but for the case of vector meson production (at the energies of 20, 40, 100 GeV respectively). From them one can conclude that the contribution of recombination diagrams to the cross-section is still larger than in the case of B_c-meson production. This explains the fact that the ratio $\sigma_{B_c^*}/\sigma_{B_c}$ in gg collisions is different from that in e^+e^- collisions, where the fragmentation mechanism is dominant.

When comparing distributions over z at different energies one can see that the form of distributions considerably changes both in the case of B_c- and of B_c^*-meson production. The observed dependence of $\sigma_{B_c^*}/\sigma_{B_c}$ shows that the contribution of the recombination diagrams decreases with the energy growth faster than the contribution of fragmentation diagrams, although at all the reasonable energies it remains significantly large.

The fragmentation and recombination contributions have different behavior over the transverse momentum (see Figs. 4c, 5c). These cross-section distributions of the gluonic B_c-meson production are shown for energies 40, 100 GeV (solid and dashed lines correspond to the total cross-section and its fragmentation part respectively). In the case of B_c^*-meson production analogous distributions are presented in Figs. 7c, 8c. From them one can conclude that the contribution of recombination diagrams remains substantial over all the kinematical region (see also Figs. 4b, 5b for B_c and Figs. 7b, 8b for B_c^*, which show the distributions over $\cos\Theta$, where Θ is the angle of $B_c(B_c^*)$ with respect to the beam axis; dashed line is the fragmentation contribution).

Comparing the distributions over $\cos\Theta$ for B_c-meson at different energies one should note that while the B_c-meson production not far from threshold is actually uniform, at

direction of initial gluons. Analogous note is also valid for the vector meson production.

The comparison of the distributions $\frac{d\hat{\sigma}_{gg\to B_c\bar{b}c}}{d\cos\Theta}$ and $\frac{d\hat{\sigma}_{gg\to B_c^*\bar{b}c}}{d\cos\Theta}$ at low energy shows that for the same energy the distribution over $\cos\Theta$ for B_c is more uniform than that for the B_c^*.

3 $B_c(B_c^*)$-meson hadronic production cross-section.

In the parton model the total cross-section for the $B_c(B_c^*)$-meson production is expressed through the subprocess cross-section in the following way:

$$\sigma_{tot}(s) = \int\limits_{(2m_b+2m_c)^2}^{s} \frac{d\hat{s}}{s} \int\limits_{-1+\frac{\hat{s}}{s}}^{1-\frac{\hat{s}}{s}} \frac{dx}{x^*}\Big(\sum_{i,j} f_a^i(x_1) f_b^j(x_2)\cdot\sigma_{ij}(\hat{s})\Big), \tag{5}$$

where $\hat{s}$—invariant mass squared of interacting partons;

x_1, x_2—portions of parton momenta in the appropriate protons;

$x = x_1 - x_2;\;\; x^* = \sqrt{x^2 + 4\hat{s}/s};$

$f_a^i(x_1)$,$f_b^j(x_2)$—parton structure functions in interacting hadrons; $\sigma_{ij}(\hat{s})$—the subprocess $ij \to B_c\bar{b}c$ cross-section.

The gluon structure functions $G(x,Q^2)$ are as follows [15]:

$$x\cdot G(x,Q^2) = K(S)\cdot \exp\left(12\sqrt{S\cdot ln(1/x)/B}\;\right)\cdot(1-x)^6,$$

where

$$\begin{aligned} &t_0 = ln(Q_0^2/\Lambda^2),\\ &t = ln(Q^2/\Lambda^2),\\ &S = ln(t/t_0),\\ &B = 33 - 2N_f, \end{aligned}$$

$$K(S) = 50.36(\exp(S) - 0.957)\exp(-7.597\sqrt{S}),$$
$$Q_0^2 = 5\ \text{GeV}^2,\;\; \Lambda = 200\ \text{MeV},\;\; N_f = 5.$$

The structure functions of valent quarks u, d in the proton ($\bar{u}$, $\bar{d}$ in the antiproton) have the following form:

$$x\cdot U(x,Q^2) = K'(S)\cdot\exp\left(4\sqrt{2}\sqrt{S\cdot ln(1/x)/B}\;\right)\cdot x^{0.65}\cdot(1-x)^3,$$
$$x\cdot D(x,Q^2) = 0.5\cdot(1-x)\cdot x\cdot U(x,Q^2),$$

where $K'(S) = 2\sqrt{S}\exp(-1.5S)$.

The structure functions of sea quarks $\bar{u}$, $\bar{d}$ in the proton (u, d in the antiproton) are equal to:

$$x\cdot\bar{U}(x,Q^2) = x\cdot\bar{D}(x,Q^2) = 0.5\cdot\sqrt{S\cdot ln(1/x)/B}\cdot x\cdot G(x,Q^2).$$

In Tab. 3 we present the values of total production cross-sections of B_c-meson S-levels

Table 3: Hadronic production cross-section of $B_c(B_c^*)$.(Bracketed is the Monte-Carlo error in the last digit.)

$n^{2S+1}L_J$	1^1S_0	1^3S_1	2^1S_0	2^3S_1
σ(40 GeV), $nb \cdot 10^{-5}$	1.07(1)	4.44(6)	0.0846(5)	0.387(5)
σ(100 GeV), $nb \cdot 10^{-3}$	6.18(6)	17.7(2)	0.873(8)	2.45(3)
σ(1.8 TeV), nb	12.2(3)	32.2(2)	2.7(1)	6.8(4)
σ(16 TeV), $nb \cdot 10^2$	1.96(8)	4.99(6)	0.42(3)	1.1(1)

The energy of 40 GeV is close to the c.m.s. energy for the fixed target experiments at HERA, calculations at $\sqrt{s} = 1.8$ TeV are made bearing in mind the experiments at Tevatron and, at last, the energy $\sqrt{s} = 16$ TeV corresponds to the conditions of pp-experiment at LHC. The energy dependence of the cross-section summed also over $\bar{B}_c$ is shown in Fig. 9.

From Tab. 3 it follows that for $\sqrt{s} = 40$ GeV the summed meson production cross-section σ_{sum} is $\sim 10^{-4}$ of the total $b\bar{b}$ production cross-section which makes the study a very complicated task in these experiments. One should note that in this case one cannot use only the $gg \to B_c \bar{b} c$ contributions and we take into account also the $q\bar{q} \to B_c \bar{b} c$ one.

There are experiments at Tevatron and LHC that will have a real possibility to discover the hadronic B_c production, because in the latter case $\frac{\sigma_{sum}}{\sigma_{b\bar{b}}}$ is $\sim 10^{-2}$. For this reason we give for the last two colliders the most interesting distributions of 1^1S_0 and 1^3S_1 production cross-sections. Note, that as our calculations have show, the cross-section at the considered energies is completely determined by gluon interaction (the suppression of quark-antiquark contribution is $\sim 10^{-2}$).

Figs.10 and 11 present the distributions for 1^1S_0 (dashed line) and 1^3S_1 (solid line) at the energy of 1.8 TeV of colliding hadrons. Distributions $\frac{d\sigma_{B_c(B_c^*)}}{dx}$ (see Fig. 11b) show that the particles are created in the central region, the cross-section dominates in the interval from -0.3 to 0.3.

From Fig. 10b it follows that the mean B_c-meson transverse momentum is not large and has the value of the order of 6 GeV. Figs. 10c, 11d, where the distributions over b- and c-quark transverse momenta are presented, show that mean transverse momenta of remaining free quarks is actually the same as that of B_c-meson.

From the distributions of Fig. 11a over the angle between the directions of motions of B_c-meson and c-quark one can see that in most cases the c-quark moves in the same direction as B_c-meson.

It is interesting to note that the distribution over the invariant mass of three final particles $M_{B_c \bar{b} c}$ both for vector and pseudoscalar mesons (Fig. 10a) shows that the cross-section is saturated in the region of $M_{B_c \bar{b} c}$ from the threshold up to the 100 GeV and that the mean value of $M_{B_c \bar{b} c}$ is of the order of 30 GeV.

The behavior of the distributions at the energy of colliding hadrons of 16 TeV is not much different from those considered above. This can be seen from Figs. 12 and 13 where the same distributions as in Figs. 10 and 11 are presented but for the energy of 16 TeV.

Conclusion

In this work we presented the calculation results for $B_c(B_c^*)$-meson hadronic production and its radial excitations production. The calculations are made in the QCD perturbation theory in the forth order over the strong coupling constant α_s^4.

The successive analysis of various diagram contributions shows that they may be divided into two types: fragmentation and recombination ones. The diagrams of the first class describe the process of b-quark fragmentation into $B_c(B_c^*)$-meson. Such process is well described on the basis of $B_c(B_c^*)$ production in e^+e^- annihilation. The differential cross-section of fragmentation contribution has simple factorized form (2). Repeating the arguments of the works, devoted to the case of e^+e^- annihilation, we have confirmed the existence of such factorization in two gluon $B_c(B_c^*)$-meson production. The results of our computer calculations for the fragmentation contribution coincide with factorized result (2). Then we showed that the fragmentation contribution in contrast to the existing point of view [16] is not dominant even in the region of large transverse momenta.

The basic contribution to the $B_c(B_c^*)$ production is related with diagrams of recombination type. The contribution of some of them falls with the energy increase by the factor of $\frac{1}{\hat{s}}$ faster than others explaining thus the strong dependence of $B_c(B_c^*)$ spectra on $\hat{s}$ (in the considered interval of $\hat{s}$). One should note that in contrast to the fragmentation contribution, where the ratio $\frac{\sigma_{B_c*}}{\sigma_{B_c}}$ is 1.3, recombination diagrams give the ratio $\frac{\sigma_{B_c*}}{\sigma_{B_c}} \sim 2.5$. Such a ratio is consistent with naive counting of spin degrees of freedom.

The considered diagrams of QCD perturbation theory are of the forth order with respect to the strong coupling constant α_s. This causes strong dependence on the definite choice of Q^2 in the argument of $\alpha_s(Q^2)$. The choice of Q^2 has to be defined by a typical virtuality in the production process. The analysis shows that this virtuality is large only in contributions, which fall faster than $\frac{1}{\hat{s}}$. In other cases, including fragmentation contribution, this virtuality is not large and is of the order of $4m_bm_c$. For this reason in cross-section estimation we used the value $\alpha_s = 0.2$. Using, for example, the quantity $\alpha_s(\hat{s})$ leads to a 7 fold decrease of the $B_c(B_c^*)$-meson cross-section. However, in this case it does not explain the disagreement between our predictions and those from ref. [16] for $B_c(B_c^*)$ total production cross-section. In [16] the same diagrams as in the present work are calculated. Both we and [16] predict the contribution $q\bar{q} \to B_c\bar{b}c$ to be small. However, in [16] the definition of Q^2 in the strong coupling constant $\alpha_s(Q^2)$ is absent. Probably, the authors of [16] have used the definition $\alpha_s(\hat{s})$. But even in this case, according to our opinion, the B_c and B_c^* production cross-section obtained in ref. [16] is too small: it is even smaller than the contribution of the fragmentation component alone [17].

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Figure captions

Fig. 1 Types of diagrams of the four free quarks gluonic production.

Fig. 2 The cross-section of the subprocesses $gg \to B_c \bar{b} c$ (blank marker) and $gg \to B_c^* \bar{b} c$ (black marker) as function of the gluonic energy. The dependence $2 \cdot 10^{-3} \cdot \sigma_{gg \to b\bar{b}}$ is presented by solid line.

Fig. 3 The cross-section distributions of the gluonic B_c-meson production for energy of 20 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum.

Fig. 4 The cross-section distributions of the gluonic B_c-meson production (solid lines) and the distributions of fragmentation part of this production (dashed lines) for energy of 40 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum;
d) z for the fragmentation contribution (dashed line) and for the fragmentation mechanism prediction (solid line).

Fig. 5 The cross-section distributions of the gluonic B_c-meson production (solid lines) and the distributions of fragmentation part of this production (dashed lines) for energy of 100 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum;
d) z for the fragmentation contribution (dashed line) and for the fragmentation mechanism prediction (solid line).

Fig. 6 The cross-section distributions of the gluonic B_c^*-meson production for energy of 20 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum.

Fig. 7 The cross-section distributions of the gluonic B_c^*-meson production (solid lines) and the distributions of fragmentation part of this production (dashed lines) for energy of 40 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum;
d) z for the fragmentation contribution (dashed line) and for the fragmentation mechanism prediction (solid line).

Fig. 8 The cross-section distributions of the gluonic B_c^*-meson production (solid lines) and

of 100 GeV (see Section 2) over:
a) z (dotted line — fragmentation mechanism prediction);
b) $\cos\Theta$;
c) the transverse momentum;
d) z for the fragmentation contribution (dashed line) and for the fragmentation mechanism prediction (solid line).

Fig. 9 The total B_c-meson hadronic production (blank marker) in nb and the $b\bar{b}$-pair hadronic production in μb (black marker).

Fig. 10 The cross-section distributions of the B_c-meson production (solid lines) and the B_c^*-meson production (dashed lines) in the process $p\bar{p} \to B_c\bar{b}c + X$ for energy of 1.8 TeV (see Section 3) over:
a) the energy of the interacting partons;
b) the transverse momentum of $B_c(B_c^*)$;
c) the transverse momentum of $\bar{b}$-quark;
d) the rapidity.

Fig. 11 The cross-section distributions of the B_c-meson production (solid lines) and the B_c^*-meson production (dashed lines) in the process $p\bar{p} \to B_c\bar{b}c + X$ for energy of 1.8 TeV (see Section 3) over:
a) the angle cosine between the directions of motions of $B_c(B_c^*)$-meson and c-quark;
b) x;
c) the modulus of the $B_c(B_c^*)$-meson momentum;
d) the transverse momentum of c-quark.

Fig. 12 The cross-section distributions of the B_c-meson production (solid lines) and the B_c^*-meson production (dashed lines) in the process $pp \to B_c\bar{b}c + X$ for energy of 16 TeV (see Section 3) over:
a) the energy of the interacting partons;
b) the transverse momentum of $B_c(B_c^*)$;
c) the transverse momentum of $\bar{b}$-quark;
d) the rapidity.

Fig. 13 The cross-section distributions of the B_c-meson production (solid lines) and the B_c^*-meson production (dashed lines) in the process $pp \to B_c\bar{b}c + X$ for energy of 16 TeV (see Section 3) over:
a) the angle cosine between the directions of motions of $B_c(B_c^*)$-meson and c-quark;
b) x;
c) the module of the $B_c(B_c^*)$-meson momentum;
d) the transverse momentum of c-quark.